Cryogenics 52 (2012) 58–65

Contents lists available at SciVerse ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics

Effect of heat transfer on the performance of thermoelectric generator-driven thermoelectric refrigerator system

Lingen Chen *, Fankai Meng, Fengrui Sun

Postgraduate School, Naval University of Engineering, Wuhan 430033, PR China

ARTICLE INFO

Article history:
Received 22 July 2009
Received in revised form 20 September 2011
Accepted 25 October 2011
Available online 11 November 2011

Keywords:
Combined thermoelectric device
Thermoelectric generator
Thermoelectric refrigerator
Heat transfer
Finite-time thermodynamics
Non-equilibrium thermodynamics

ABSTRACT

A model of thermoelectric generator-driven thermoelectric refrigerator with external heat transfer is proposed. The performance of the combined thermoelectric refrigerator device obeying Newton's heat transfer law is analyzed using the combination of finite time thermodynamics and non-equilibrium thermodynamics. Two analytical formulae for cooling load vs. working electrical current, and the coefficient of performance (COP) vs. working electrical current, are derived. For a fixed total heat transfer surface area of four heat exchangers, the allocations of the heat transfer surface area among the four heat exchangers are optimized for maximizing the cooling load and the coefficient of performance (COP) of the combined thermoelectric refrigerator device. For a fixed total number of thermoelectric elements, the ratio of number of thermoelectric elements of the generator to the total number of thermoelectric elements is also optimized for maximizing both the cooling load and the COP of the combined thermoelectric refrigerator device. The influences of thermoelectric element allocation and heat transfer area allocation are analyzed by detailed numerical examples. Optimum working electrical current for maximum cooling load and COP at different total number of thermoelectric elements and different total heat transfer area are obtained, respectively.

1. Introduction

Semiconductor thermoelectric power generation, based on the Seebeck effect, and semiconductor thermoelectric cooling, based on the Peltier effect, have very interesting capabilities with respect to conventional power generation and cooling systems [1–3]. The absence of moving components results in an increase of reliability, a reduction of maintenance, and an increase of system life; the modularity allows for application in a wide-scale range without significant losses in performance; the absence of a working fluid avoids environmental dangerous leakage; and the noise reduction appears also to be an important feature. Thermoelectric generator and refrigerator have been used in military, aerospace, instrument, and industrial or commercial products, as a power generation or cooling devices for specific purposes. Many researchers are concerned about the physical properties of thermoelectric material and the manufacturing technique of thermoelectric modules. In addition to the improvement of the thermoelectric material and module, the system analysis and optimization of thermoelectric generator and refrigerator are equally important in designing high-performance thermoelectric generators and refrigerators.

In general, the conventional non-equilibrium thermodynamics [1,4] is used to analyze the performance of single-stage one- or multiple-element thermoelectric generators [5–13] and refrigerators [14–25]. Non-equilibrium thermodynamics is a progress of classical thermodynamics, it considers some specific phenomena such as Seebeck effect and Peltier effect. All objects of these researches are independent thermoelectric devices, that is, they generate direct-current power source for users (thermoelectric generator) or need a direct-current power source to provide direct current (thermoelectric refrigerator). In some special fields, the heat rejected from the thermal machine may drive a thermoelectric refrigerator through the use of a thermoelectric generator, so that the thermoelectric refrigerator does not need an independent power source. Such a new system is different from the traditional thermoelectric systems merely consisting of a thermoelectric generator and a refrigerator. These systems dispense with complicated pipelines and heat insulation, so they can be used in many special fields such as aircraft and submarine. Chen et al. [26] and Khattab and El Shenawy [27] built a model of this kind of combined system, i.e. single-stage thermoelectric refrigerator driven by single-stage thermoelectric generator, and analyzed the performance of the device.

The theory of finite time thermodynamics or entropy generation minimization [28–35] is a powerful tool for performance analysis and optimization of practice thermodynamic processes and

* Corresponding author. Tel.: +86 27 83615046; fax: +86 27 83638709.
E-mail addresses: lingenchen@hotmail.com, lgchenna@yahoo.com (L. Chen).

0011-2275/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cryogenics.2011.10.007

Nomenclature

A	coefficient of system stable working electrical current equation
F	heat transfer surface areas of heat exchanger
f	heat transfer surface area ratio
I	working electrical current (A)
K	thermal conductance of a semiconductor couple (W/K)
k	heat transfer coefficient of heat exchanger (W/K)
M	total number of thermoelectric elements pairs of whole device
m	number of thermoelectric elements pairs of thermoelectric generator
n	number of thermoelectric elements pairs of thermoelectric refrigerator
T	temperature (K)
Q	rate at which heat is transferred (W)
R	total internal electrical resistance of a semiconductor couple (Ω)
x	ratio of number of thermoelectric element pairs of the thermoelectric generator to total number of thermoelectric element pairs of the combined irreversible device

Greek symbols

α	Seebeck coefficients of P- and N- type semiconductor legs
ε	coefficient of performance (COP) of combined thermoelectric refrigerator device

Subscripts

1	parameter of thermoelectric generator
2	parameter of thermoelectric refrigerator
$H1$	heat source of thermoelectric generator
$H2$	heat sink of thermoelectric refrigerator
$L1$	heat sink of thermoelectric generator
$L2$	heat source of thermoelectric refrigerator
s	practical solution of working electrical current equation
opt	optimum parameter

devices. Finite time thermodynamics or entropy generation minimization is the method of modeling and optimization of various thermodynamic processes and devices that owe their thermodynamic imperfection to heat transfer, mass transfer, and fluid flow and other transport processes. It bridges the gaps not only between thermodynamic and heat transfer, mass transfer, fluid mechanics, and other transport science, but also between the physics and the engineering. It thermodynamically optimize performance of real finite-time and/or finite-size thermodynamic systems with the irreversibilities of heat transfer, fluid flow and mass transfer toward decreasing the irreversibility of the total system. Some authors have investigated the performance of thermoelectric generators [36–48] and thermoelectric refrigerator [49–57] using the combination of finite time thermodynamics and non-equilibrium thermodynamics. They analyzed the effect of finite-rate heat transfer between the thermoelectric device and its external heat reservoirs on the performance of single-element single-stage thermoelectric generators [36–43] and refrigerator [49–52]. They also investigated the characteristics of single-stage multi-element thermoelectric generators [44–48] and thermoelectric refrigerator [53–57] with the irreversibility of finite rate heat transfer, Joulean heat inside the thermoelectric device, and the heat leak through the thermoelectric couple leg. However, all of those were performed only for independent thermoelectric devices. There has been no investigation concerning the performance analysis and optimization for single-stage thermoelectric refrigerator driven by single-stage thermoelectric generator published in the open literature.

On the basis of the exo-reversible model of a single-stage thermoelectric refrigerator driven by a single-stage thermoelectric generator without external irreversibility built in Refs. [26,27], a model of thermoelectric generator-driven thermoelectric refrigerator with external heat transfer is built. The performance of the combined thermoelectric refrigerator device obeying Newton's heat transfer law is analyzed using the combination of finite time thermodynamics and non-equilibrium thermodynamics. Two analytical formulae for cooling load vs. working electrical current, and the coefficient of performance (COP) vs. working electrical current, are derived. For a fixed total heat transfer surface area of four heat exchangers, the allocations of the heat transfer surface area among the four heat exchangers are optimized for maximizing the cooling load and the coefficient of performance (COP) of the combined thermoelectric refrigerator device. For a fixed total number of thermoelectric elements, the ratio of number of thermoelectric elements of the generator to the total number of thermoelectric elements is also optimized for maximizing both the cooling load and the COP of the combined thermoelectric refrigerator device. The influences of thermoelectric element allocation and heat transfer area allocation are analyzed by detailed numerical examples. Optimum working electrical current for maximum cooling load and COP at different total number of thermoelectric elements and different total heat transfer area are given, respectively.

2. Model of a thermoelectric generator-driven thermoelectric refrigerator system

A schematic diagram of a thermoelectric generator-driven thermoelectric refrigerator device is shown in Fig. 1. The device consists of an irreversible single-stage multi-element thermoelectric generator and an irreversible single-stage multi-element thermoelectric refrigerator in series with internal and external irreversibilities. The direct-current power source of the refrigerator is the direct-current power output of the generator.

The irreversible thermoelectric generator is composed of m pairs of thermoelectric elements. Each element is composed of P-type and N-type semiconductor legs. The thermoelectric power generation element is assumed to be insulated, both electrically and thermally, from its surroundings, except at the junction-reservoir contacts. The internal irreversibility is caused by Joulean electrical resistive loss and heat conduction loss through the semiconductor between the hot and cold junctions. The Joulean loss generates an internal heat I^2R, where R is the total internal electrical resistance of the semiconductor couple and I is the electrical current generating from the semiconductor couple. The conduction heat loss is $K(T'_{H1} - T'_{L1})$, where K is the thermal conductance of the semiconductor couple, T'_{H1} is the hot junction temperature, and T'_{L1} is the cold junction temperature. Finite rate heat transfers, i.e. the temperature differences $(T_{H1} - T'_{H1})$ and $(T'_{L1} - T_{L1})$, where T_{H1} and T_{L1} are the temperatures of the heat source and heat sink of the thermoelectric generator, respectively, cause the external irreversibility. For the thermoelectric generator, the rate of heat transfer at the hot junction is Q_{H1}, and the rate of heat transfer at the cold junction is Q_{L1}.

The irreversible thermoelectric refrigerator is composed of n pairs of thermoelectric elements. Each element is composed of

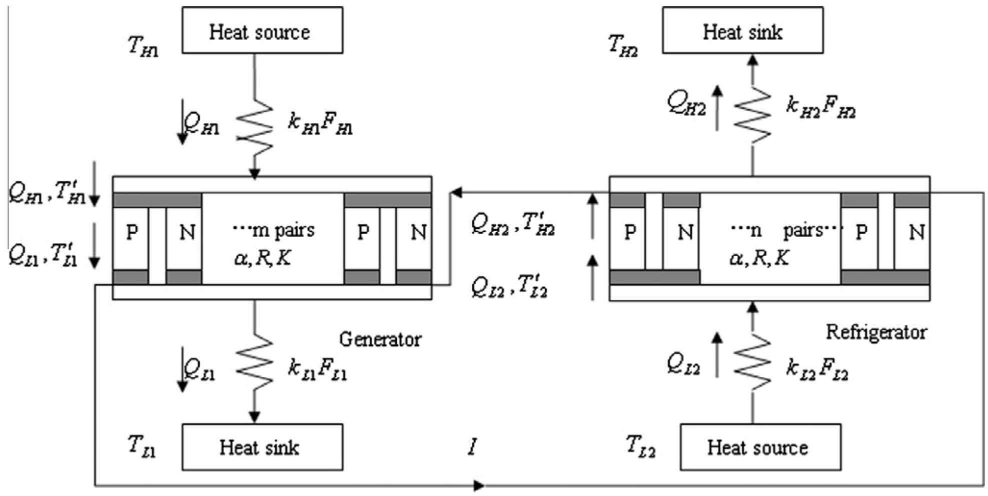

Fig. 1. Schematic diagram of the combined thermoelectric device.

P-type and N-type semiconductor legs. The thermoelectric refrigerating element is assumed to be insulated, both electrically and thermally, from its surroundings, except at the junction-reservoir contacts. The internal irreversibility is caused by Joulean electrical resistive loss and heat conduction loss through the semiconductor between the hot and cold junctions. The Joulean loss generates an internal heat I^2R, where R is the total internal electrical resistance of the semiconductor couple and I is the electrical current generating from the semiconductor couple. The conduction heat loss is $K(T'_{H2} - T'_{L2})$, where K is the thermal conductance of the semiconductor couple, T'_{H2} is the hot junction temperature, and T'_{L2} is the cold junction temperature. Finite rate heat transfers, i.e. the temperature differences $(T_{H2} - T'_{H2})$ and $(T'_{L2} - T_{L2})$, where T_{H2} and T_{L2} are the temperatures of the heat sink and heat source of the thermoelectric refrigerator, respectively, cause the external irreversibility. For the thermoelectric refrigerator, the rate of heat transfer at the hot junction is Q_{H2}, and the rate of heat transfer at the cold junction is Q_{L2}.

Assume that the four heat exchangers among the hot and cold junctions of the thermoelectric refrigerator, thermoelectric generator and their respective reservoirs are counter-flow, and the heat conductance (product of heat transfer coefficient and heat transfer surface area) of the heat exchangers are $k_{H1}F_{H1}$, $k_{L1}F_{L1}$, $k_{H2}F_{H2}$ and $k_{L2}F_{L2}$, respectively, where k_{H1}, k_{L1}, k_{H2} and k_{L2} are the heat transfer coefficients of the four heat exchangers, respectively, and F_{H1}, F_{L1}, F_{H2} and F_{L2} are the heat transfer surface areas of the four heat exchangers, respectively.

The total number (M) of thermoelectric element pairs of the irreversible combined thermoelectric device is finite and $M = m + n$ holds. The total heat transfer surface area (F) of the four heat exchangers of the irreversible combined thermoelectric device is finite and $F = F_{H1} + F_{L1} + F_{H2} + F_{L2}$ holds.

Assuming that the heat transfers among the hot and cold junctions of the thermoelectric generator and the thermoelectric refrigerator and their respective reservoirs obey Newton's law gives:

$$Q_{H1} = k_{H1}F_{H1}(T_{H1} - T'_{H1}) = m\left[\alpha I T_{H1} + K(T'_{H1} - T'_{L1}) - \frac{1}{2}I^2R\right] \tag{1}$$

$$Q_{L1} = k_{L1}F_{L1}(T'_{L1} - T_{L1}) = m\left[\alpha I T_{L1} + K(T'_{H1} - T'_{L1}) + \frac{1}{2}I^2R\right] \tag{2}$$

$$Q_{H2} = k_{H2}F_{H2}(T'_{H2} - T_{H2}) = n\left[\alpha I T_{H2} - K(T'_{H2} - T'_{L2}) + \frac{1}{2}I^2R\right] \tag{3}$$

$$Q_{L2} = k_{L2}F_{L2}(T_{L2} - T'_{L2}) = n\left[\alpha I T_{L2} - K(T'_{H2} - T'_{L2}) - \frac{1}{2}I^2R\right] \tag{4}$$

where $\alpha = \alpha_P - \alpha_N$, α_P and α_N are the Seebeck coefficients of the P- and N- type semiconductor legs for each thermoelectric power generation and refrigeration element.

3. Performance analysis

Combining Eq. (1) with Eq. (2) gives the hot junction temperature T'_{H1}, and the cold junction temperature T'_{L1} of the thermoelectric generator:

$$T'_{H1} = \frac{0.5\alpha R m^2 I^3 - (0.5m + m^2K)RI^2 + m\alpha T_{H1}I - mK(k_{H1}F_{H1}T_{H1} + k_{L1}F_{L1}T_{L1}) - k_{H1}F_{H1}k_{L1}F_{L1}T_{H1}}{m^2\alpha^2I^2 + m\alpha(k_{H1}F_{H1} - k_{L1}F_{L1})I - mK(k_{H1}F_{H1} + k_{L1}F_{L1}) - k_{H1}F_{H1}k_{L1}F_{L1}} \tag{5}$$

$$T'_{L1} = \frac{-0.5\alpha R m^2 I^3 - (0.5m + m^2K)RI^2 - m\alpha T_{H1}I - mK(k_{H1}F_{H1}T_{H1} + k_{L1}F_{L1}T_{L1}) - k_{H1}F_{H1}k_{L1}F_{L1}T_{H1}}{m^2\alpha^2I^2 + m\alpha(k_{H1}F_{H1} - k_{L1}F_{L1})I - mK(k_{H1}F_{H1} + k_{L1}F_{L1}) - k_{H1}F_{H1}k_{L1}F_{L1}} \tag{6}$$

Combining Eq. (3) with Eq. (4) gives the hot junction temperature T'_{H2} and the cold junction temperature T'_{L2} of the thermoelectric refrigerator.

$$T'_{H2} = \frac{-0.5\alpha R n^2 I^3 - (0.5n + n^2K)RI^2 - n\alpha T_{H2}I - nK(k_{H2}F_{H2}T_{H2} + k_{L2}F_{L2}T_{L2}) - k_{H2}F_{H2}k_{L2}F_{L2}T_{H2}}{n^2\alpha^2I^2 + n\alpha(k_{L2}F_{L2} - k_{H2}F_{H2})I - nK(k_{H2}F_{H2} + k_{L2}F_{L2}) - k_{H2}F_{H2}k_{L2}F_{L2}} \tag{7}$$

$$T'_{L2} = \frac{-0.5\alpha R n^2 I^3 - (0.5n + n^2 K) R I^2 + n\alpha T_{H2} I - nK(k_{H2}F_{H2}T_{H2} + k_{L2}F_{L2}T_{L2}) - k_{H2}F_{H2}k_{L2}F_{L2}T_{H2}}{n^2\alpha^2 I^2 + n\alpha(k_{L2}F_{L2} - k_{H2}F_{H2})I - nK(k_{H2}F_{H2} + k_{L2}F_{L2}) - k_{H2}F_{H2}k_{L2}F_{L2}} \tag{8}$$

Substituting Eqs. (5)–(8) into Eqs. (1)–(4) yields:

$$\begin{aligned} Q_{H1} = k_{H1}F_{H1}\{T_{H1} - [&0.5\alpha R m^2 I^3 - (0.5m + m^2 K) R I^2 + m\alpha T_{H1} I \\ &- mK(k_{H1}F_{H1}T_{H1} + k_{L1}F_{L1}T_{L1}) \\ &- k_{H1}F_{H1}k_{L1}F_{L1}T_{H1}]/[m^2\alpha^2 I^2 + m\alpha(k_{H1}F_{H1} - k_{L1}F_{L1})I \\ &- mK(k_{H1}F_{H1} + k_{L1}F_{L1}) - k_{H1}F_{H1}k_{L1}F_{L1}]\} \end{aligned} \tag{9}$$

$$\begin{aligned} Q_{L1} = k_{L1}F_{L1}\{[&-0.5\alpha R m^2 I^3 - (0.5m + m^2 K) R I^2 - m\alpha T_{H1} I \\ &- mK(k_{H1}F_{H1}T_{H1} + k_{L1}F_{L1}T_{L1}) \\ &- k_{H1}F_{H1}k_{L1}F_{L1}T_{H1}]/[m^2\alpha^2 I^2 + m\alpha(k_{H1}F_{H1} - k_{L1}F_{L1})I \\ &- mK(k_{H1}F_{H1} + k_{L1}F_{L1}) - k_{H1}F_{H1}k_{L1}F_{L1}] - T_{L1}\} \end{aligned} \tag{10}$$

$$\begin{aligned} Q_{H2} = k_{H2}F_{H2}\{T_{H2} - [&-0.5\alpha R n^2 I^3 - (0.5n + n^2 K) R I^2 - n\alpha T_{H2} I \\ &- nK(k_{H2}F_{H2}T_{H2} + k_{L2}F_{L2}T_{L2}) \\ &- k_{H2}F_{H2}k_{L2}F_{L2}T_{H2}]/[n^2\alpha^2 I^2 + n\alpha(k_{L2}F_{L2} - k_{H2}F_{H2})I \\ &- nK(k_{H2}F_{H2} + k_{L2}F_{L2}) - k_{H2}F_{H2}k_{L2}F_{L2}]\} \end{aligned} \tag{11}$$

$$\begin{aligned} Q_{L2} = k_{L2}F_{L2}\{[&-0.5\alpha R n^2 I^3 - (0.5n + n^2 K) R I^2 + n\alpha T_{H2} I \\ &- nK(k_{H2}F_{H2}T_{H2} + k_{L2}F_{L2}T_{L2}) \\ &- k_{H2}F_{H2}k_{L2}F_{L2}T_{H2}]/[n^2\alpha^2 I^2 + n\alpha(k_{L2}F_{L2} - k_{H2}F_{H2})I \\ &- nK(k_{H2}F_{H2} + k_{L2}F_{L2}) - k_{H2}F_{H2}k_{L2}F_{L2}] - T_{L2}\} \end{aligned} \tag{12}$$

The overall system is a closed loop circuit, and the heat flow of the system is in balance, one has:

$$Q_{H1} + Q_{L2} = Q_{L1} + Q_{H2} \tag{13}$$

Substituting Eqs. (9)–(12) into Eq. (13) and re-arranging the results yields the equation that the system stable working electrical current should be satisfied:

$$A_4 I^4 + A_3 I^3 + A_2 I^2 + A_1 I + A_0 = 0 \tag{14}$$

where

$$A_4 = \alpha^3 m^2 n^2 R(k_{L1}F_{L1} - k_{H1}F_{H1} - k_{L2}F_{L2} + k_{H2}F_{H2}) \tag{15}$$

$$\begin{aligned} A_3 = \alpha^2 mn[&mn(2k_{H2}F_{H2}KR + 2k_{H2}F_{H2}T_{H2}\alpha^2 + 2k_{L2}F_{L2}KR \\ &+ 2k_{H1}F_{H1}KR + 2k_{L2}F_{L2}T_{L2}a^2 + 2\alpha^2 k_{L1}F_{L1}T_{L1} + 2k_{L1}F_{L1}KR \\ &+ 2\alpha^2 k_{H1}F_{H1}T_{H1}) + m(k_{H2}F_{H2}Rk_{H1}F_{H1} - k_{H2}F_{H2}Rk_{L1}F_{L1} \\ &+ k_{L2}F_{L2}Rk_{L1}F_{L1} - k_{L2}F_{L2}Rk_{H1}F_{H1} + 2k_{L2}F_{L2}k_{H2}F_{H2}R) \\ &+ n(-k_{H2}F_{H2}Rk_{L1}F_{L1} + 2k_{H1}F_{H1}k_{L1}F_{L1}R - k_{L2}F_{L2}Rk_{H1}F_{H1} \\ &+ k_{L2}F_{L2}Rk_{L1}F_{L1} + k_{H2}F_{H2}Rk_{H1}F_{H1})] \end{aligned} \tag{16}$$

$$\begin{aligned} A_2 = \alpha[&m^2 n(-3k_{L1}F_{L1}KRk_{H2}F_{H2} - 2\alpha^2 k_{L1}F_{L1}T_{L1}k_{H2}F_{H2} \\ &+ 2\alpha^2 k_{L1}F_{L1}T_{L1}k_{L2}F_{L2} + 2\alpha^2 k_{H1}F_{H1}T_{H1}k_{L2}F_{L2} \\ &+ k_{L1}F_{L1}KRk_{L2}F_{L2} - 2\alpha^2 k_{H1}F_{H1}T_{H1}k_{H2}F_{H2} \\ &- 2k_{L2}F_{L2}T_{L2}\alpha^2 k_{H2}F_{H2} + 2k_{H2}F_{H2}T_{H2}\alpha^2 k_{L2}F_{L2} \\ &- k_{H1}F_{H1}KRk_{H2}F_{H2} + 3k_{H1}F_{H1}KRk_{L2}F_{L2}) \\ &+ mn^2(-k_{L1}F_{L1}KRk_{L2}F_{L2} + 2\alpha^2 k_{L2}F_{L2}T_{L2}k_{H1}F_{H1} \\ &+ 3k_{H1}F_{H1}KRk_{L2}F_{L2} - 2\alpha^2 k_{H1}F_{H1}T_{H1}k_{L1}F_{L1} + 2\alpha^2 k_{H2}F_{H2}T_{H2}k_{H1}F_{H1} \\ &- k_{L2}F_{L2}T_{L2}\alpha^2 k_{L1}F_{L1} + k_{H1}F_{H1}KRk_{H2}F_{H2} - 3k_{L1}F_{L1}KRk_{H2}F_{H2} \\ &+ 2\alpha^2 k_{L1}F_{L1}T_{L1}k_{H1}F_{H1} - 2k_{H2}F_{H2}T_{H2}\alpha^2 k_{L1}F_{L1}) \\ &+ m^2(-k_{L1}F_{L1}Rk_{H2}F_{H2}k_{L2}F_{L2} - k_{H1}F_{H1}Rk_{H2}F_{H2}k_{L2}F_{L2}) \\ &+ n^2(k_{L2}F_{L2}Rk_{L1}F_{L1}k_{H1}F_{H1} - k_{H2}F_{H2}Rk_{L1}F_{L1}k_{H1}F_{H1}) \\ &+ mn(2k_{L2}F_{L2}Rk_{L1}F_{L1}k_{H1}F_{H1} + 2k_{L1}F_{L1}Rk_{H2}F_{H2}k_{L2}F_{L2} \\ &+ 2k_{H2}F_{H2}Rk_{L1}F_{L1}k_{H1}F_{H1} + 2k_{H1}F_{H1}Rk_{H2}F_{H2}k_{L2}F_{L2})] \end{aligned} \tag{17}$$

$$\begin{aligned} A_1 = &-2m^2 nK(k_{L2}F_{L2} + k_{H2}F_{H2})(k_{L1}F_{L1}KR \\ &+ Kk_{H1}F_{H1}R + \alpha^2 k_{L1}F_{L1}T_{L1} + \alpha^2 k_{H1}F_{H1}T_{H1}) \\ &- 2m\ n^2 K(k_{H1}F_{H1} + k_{L1}F_{L1})(KRk_{L2}F_{L2} + KRk_{H2}F_{H2} \\ &+ \alpha^2 k_{H2}F_{H2}T_{H2} + \alpha^2 k_{L2}F_{L2}T_{L2}) \\ &- 2m^2 k_{L2}F_{L2}k_{H2}F_{H2}(KRk_{L1}F_{L1} \\ &+ KRk_{H1}F_{H1} + \alpha^2 k_{L1}F_{L1}T_{L1} + \alpha^2 k_{H1}F_{H1}T_{H1}) \\ &- 2n^2 k_{L1}F_{L1}k_{H1}F_{H1}(KRk_{L2}F_{L2} + KRk_{H2}F_{H2} \\ &+ a^2 k_{H2}F_{H2}T_{H2} + \alpha^2 k_{L2}F_{L2}T_{L2}) \\ &+ 2mn[\alpha^2(k_{H1}F_{H1}k_{L1}F_{L1}k_{H2}F_{H2}T_{H1} \\ &- k_{L2}F_{L2}k_{H2}F_{H2}k_{H1}F_{H1}T_{L2} + k_{L1}F_{L1}k_{H1}F_{H1}k_{L2}F_{L2}T_{L1} \\ &- k_{H2}F_{H2}k_{L2}F_{L2}k_{L1}F_{L1}T_{H2} - k_{L1}F_{L1}k_{H1}F_{H1}k_{H2}F_{H2}T_{L1} \\ &+ k_{L2}F_{L2}k_{H2}F_{H2}k_{L1}F_{L1}T_{L2} - k_{H1}F_{H1}k_{L1}F_{L1}k_{L2}F_{L2}T_{H1} \\ &+ k_{H2}F_{H2}k_{L2}F_{L2}k_{H1}F_{H1}T_{H2}) - RK(k_{H2}F_{H2}k_{L1}F_{L1}k_{H1}F_{H1} \\ &+ k_{L2}F_{L2}k_{H2}F_{H2}k_{H1}F_{H1} + k_{L2}F_{L2}k_{L1}F_{L1}k_{H1}F_{H1} \\ &+ k_{L1}F_{L1}k_{L2}F_{L2}k_{H2}F_{H2})] - 2mRk_{H1}F_{H1}k_{L1}F_{L1}k_{H2}F_{H2}k_{L2}F_{L2} \\ &- 2nRk_{L2}F_{L2}k_{H2}F_{H2}k_{L1}F_{L1}k_{H1}F_{H1} \end{aligned} \tag{18}$$

$$\begin{aligned} A_0 = 2mn(&Kk_{L1}F_{L1}k_{H1}F_{H1}T_{H1}k_{H2}F_{H2} - Kk_{L1}F_{L1}k_{H1}F_{H1}T_{L1}k_{H2}F_{H2} \\ &+ Kk_{L1}F_{L1}k_{H1}F_{H1}T_{H1}k_{L2}F_{L2} - Kk_{L1}F_{L1}k_{H1}F_{H1}T_{L1}k_{L2}F_{L2} \\ &- Kk_{L2}F_{L2}k_{H2}F_{H2}T_{H2}k_{L1}F_{L1} + Kk_{L2}F_{L2}k_{H2}F_{H2}T_{L2}k_{H1}F_{H1} \\ &+ Kk_{L2}F_{L2}T_{L2}k_{H2}F_{H2}k_{L1}F_{L1} - Kk_{L2}F_{L2}k_{H2}F_{H2}T_{H2}k_{H1}F_{H1}) \\ &+ 2m(k_{H1}F_{H1}k_{L1}F_{L1}k_{H2}F_{H2}k_{L2}F_{L2}T_{H1} \\ &- k_{L1}F_{L1}k_{H1}F_{H1}k_{H2}F_{H2}k_{L2}F_{L2}T_{L1}) \\ &+ 2n(k_{L2}F_{L2}T_{L2}k_{H2}F_{H2}k_{L1}F_{L1}k_{H1}F_{H1} \\ &- k_{H2}F_{H2}k_{L2}F_{L2}k_{L1}F_{L1}k_{H1}F_{H1}T_{H2}) \end{aligned} \tag{19}$$

For the given parameters, one can obtain four theoretical solutions by solving Eq. (14). Analysis shown that there is only one solution I_s, which satisfies $I > 0$, $Q_{H1} > 0$, $Q_{L1} > 0$, $Q_{H2} > 0$, and $Q_{L2} > 0$. Upon that one has the cooling load and COP of the combined thermoelectric device as follows:

$$\begin{aligned} Q_{L2} = k_{L2}F_{L2}\Big\{\Big[&-0.5\alpha R n^2 I_s^3 - (0.5n + n^2 K) R I_s^2 + n\alpha T_{H2} I_s - nK(k_{H2}F_{H2}T_{H2} \\ &+ k_{L2}F_{L2}T_{L2}) - k_{H2}F_{H2}k_{L2}F_{L2}T_{H2}\Big]/\Big[n^2\alpha^2 I_s^2 + n\alpha(k_{L2}F_{L2} - k_{H2}F_{H2})I_s \\ &-(k_{H2}F_{H2} + k_{L2}F_{L2}) - k_{H2}F_{H2}k_{L2}F_{L2}\Big] - T_{L2}\Big\} \end{aligned} \tag{20}$$

$$\begin{aligned}\varepsilon &= Q_{L2}/Q_{H1}\\ &= \frac{k_{L2}F_{L2}\left\{\left[-0.5\alpha Rn^2I_s^3-(0.5n+n^2K)RI_s^2+n\alpha T_{H2}I_s-nK(k_{H2}F_{H2}T_{H2}+k_{L2}F_{L2}T_{L2})-k_{H2}F_{H2}k_{L2}F_{L2}T_{H2}\right]/\left[n^2\alpha^2I_s^2+n\alpha(k_{L2}F_{L2}-k_{H2}F_{H2})I_s-nK(k_{H2}F_{H2}+k_{L2}F_{L2})-k_{H2}F_{H2}k_{L2}F_{L2}\right]-T_{L2}\right\}}{k_{H1}F_{H1}\left\{T_{H1}-\left[0.5\alpha Rm^2I_s^3-(0.5m+m^2K)RI_s^2+m\alpha T_{H1}I_s-mK(k_{H1}F_{H1}T_{H1}+k_{L1}F_{L1}T_{L1})-k_{H1}F_{H1}k_{L1}F_{L1}T_{H1}\right]/\left[m^2\alpha^2I_s^2+m\alpha(k_{H1}F_{H1}-k_{L1}F_{L1})I_s-mK(k_{H1}F_{H1}+k_{L1}F_{L1})-k_{H1}F_{H1}k_{L1}F_{L1}\right]\right\}}\end{aligned} \tag{21}$$

Obviously, besides the performance parameters of thermoelectric element pairs (α, R and K), parameters concerning the heat transfer (k_{H1}, k_{L1}, k_{H2}, k_{L2}, F_{H1}, F_{L1}, F_{H2} and F_{L2}) would have influences on the device performance.

If $k_{H1}F_{H1} = k_{L1}F_{L1} = k_{H2}F_{L2} = k_{L2}F_{L2} \to \infty$, $T_{H1} = T'_{H1}$, $T_{L1} = T'_{L1}$, $T_{H2} = T'_{H2}$ and $T_{L2} = T'_{L2}$, Eqs. (20) and (21) become the results of conventional non-equilibrium thermodynamic analysis [26,27].

4. Numerical examples

4.1. Design variables and fixed parameters

For independent thermoelectric generator and thermoelectric refrigerator devices, there is an optimum heat transfer area allocation between the high temperature side and the low temperature

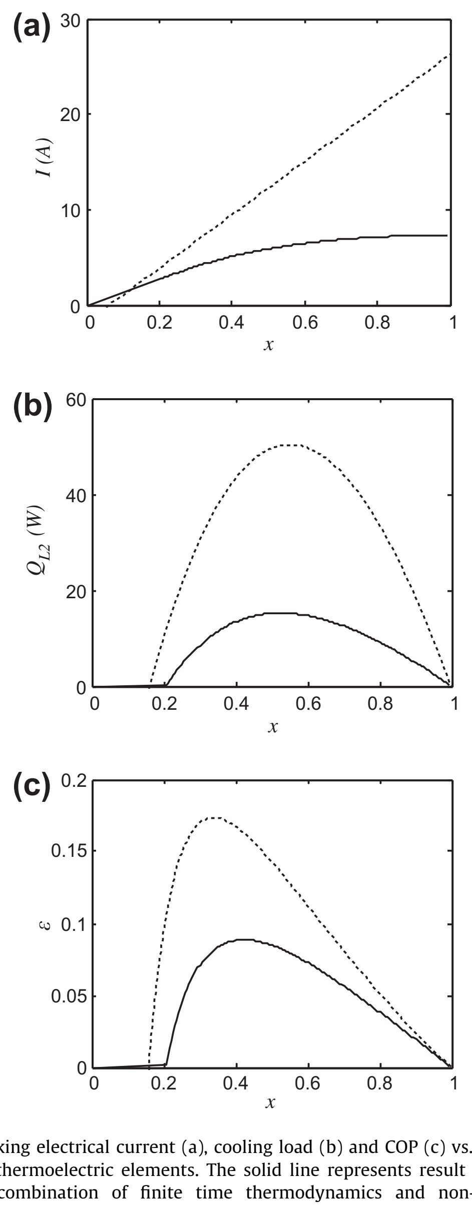

Fig. 2. Working electrical current (a), cooling load (b) and COP (c) vs. the ratio of number of thermoelectric elements. The solid line represents result obtained by using the combination of finite time thermodynamics and non-equilibrium thermodynamics. The dotted line represents result obtained by using non-equilibrium thermodynamics, i.e. effects of heat transfer are not taken into account.

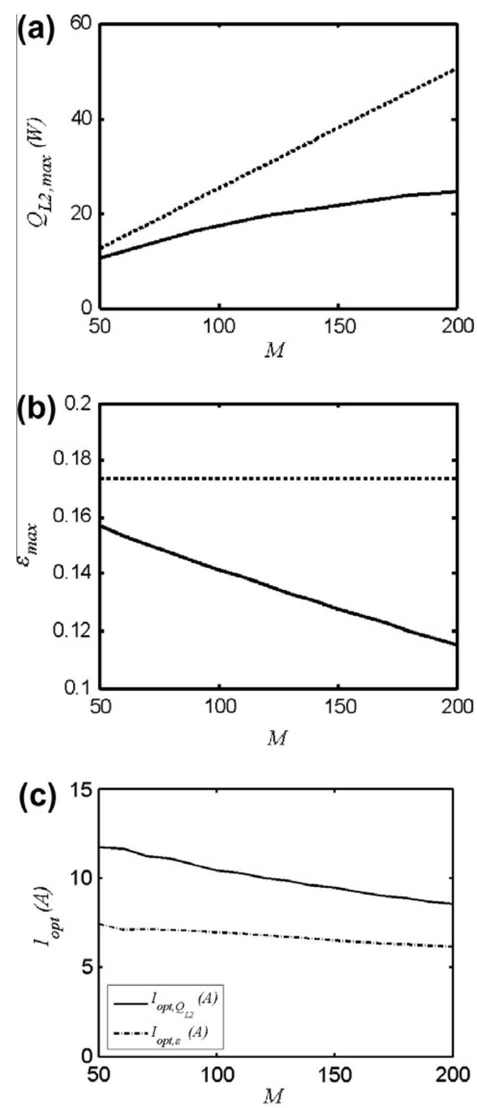

Fig. 3. Maximum cooling load (a), maximum COP (b) and optimum working electrical currents (c) vs. total number of thermoelectric elements. In (a) and (b), the solid line represents result obtained by using the combination of finite time thermodynamics and non-equilibrium thermodynamics while the dotted line represents result obtained by using non-equilibrium thermodynamics, i.e. effects of heat transfer are not taken into account. In (c), the solid line represents optimum working electrical current for maximum cooling load and the dash dot line represents optimum working electrical current for maximum COP.

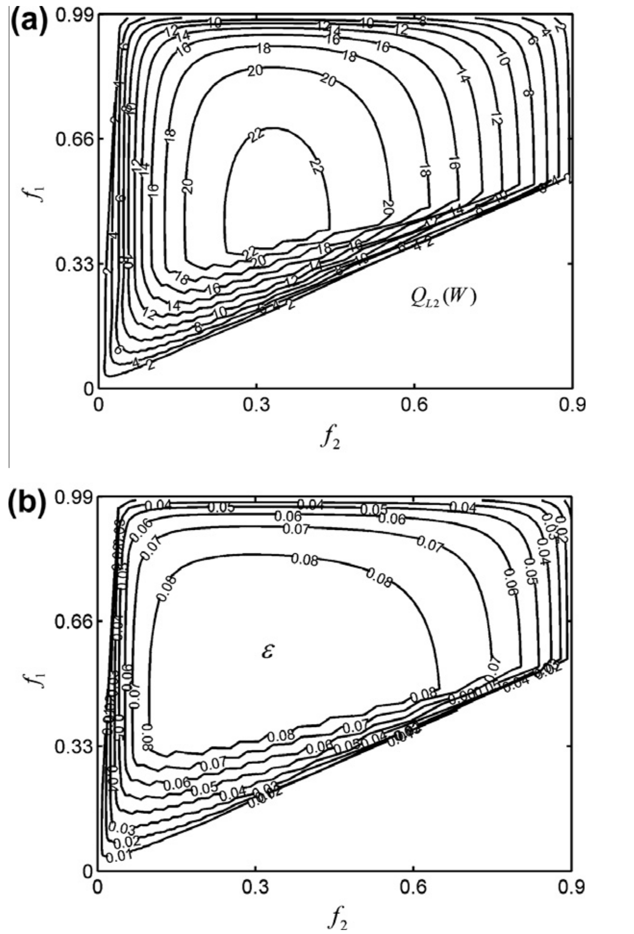

Fig. 4. Contour maps of the cooling load (a) and COP (b) vs. ratios of heat transfer surface area. f_1 is generator heat transfer surface area ratio, and f_2 is refrigerator heat transfer surface area ratio.

side heat exchangers for the fixed total heat transfer area of the thermoelectric generator or thermoelectric refrigerator. For the combined thermoelectric device, besides optimum heat transfer area allocation between the high temperature side and the low temperature side, there is an optimum heat transfer area allocation between the thermoelectric generator and the thermoelectric refrigerator for the fixed total heat transfer area of the whole device.

In order to describe the allocation of the heat transfer area, three ratios of heat transfer surface area are defined: total heat transfer surface area ratio $f = F_1/F$, where $F_1 = F_{H1} + F_{L1}$, i.e. the ratio of the heat transfer surface area of the thermoelectric generator to the total heat transfer surface area of the combined irreversible device; generator heat transfer surface area ratio $f_1 = F_{H1}/F_1$, i.e. the ratio of the heat transfer surface area of the high-temperature side heat exchangers of the thermoelectric generator to the total heat transfer surface area of the thermoelectric generator; and refrigerator heat transfer surface area ratio $f_2 = F_{H2}/F_2$, where $F_2 = F_{H2} + F_{L2}$, i.e. the ratio of the heat transfer surface area of the high-temperature side heat exchangers of the thermoelectric refrigerator to the total heat transfer surface area of the thermoelectric refrigerator. Then, one has $F_{H1} = ff_1F$, $F_{L1} = f(1-f_1)F$, $F_{H2} = (1-f)f_2F$ and $F_{L2} = (1-f)(1-f_2)F$.

In order to describe the allocation of the thermoelectric element pairs, one ratio of numbers of thermoelectric element pairs is defined: $x = m/M$, i.e. the ratio of number of thermoelectric element pairs of the thermoelectric generator to total number of thermoelectric element pairs of the combined irreversible device. Then, one has $m = xM$ and $n = (1-x)M$.

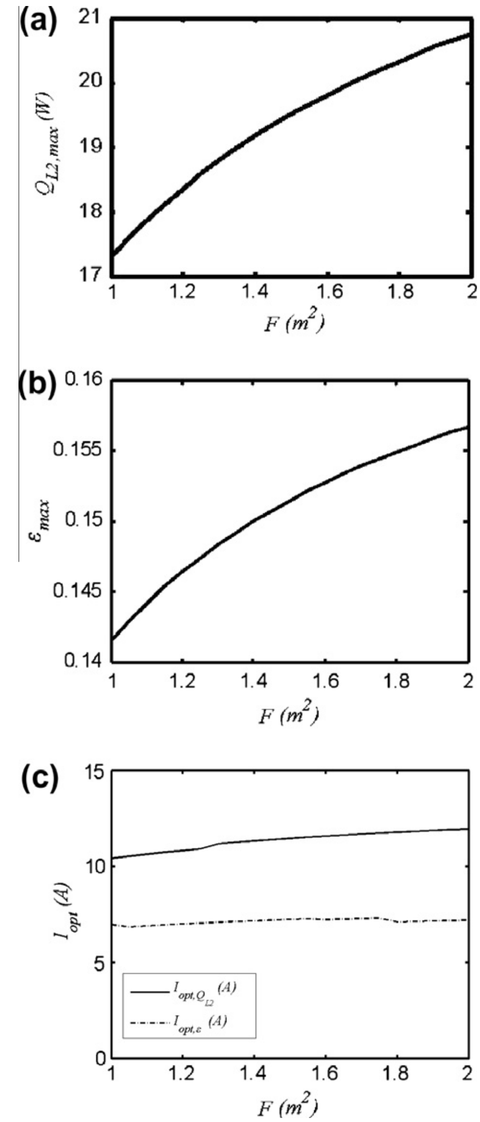

Fig. 5. Maximum cooling load (a), maximum COP (b) and optimum working electrical currents (c) vs. total heat transfer surface area. The solid line represents optimum working electrical current for maximum cooling load and the dash dot line represents optimum working electrical current for maximum COP.

Obviously, value ranges of the variables x, f, f_1, f_2 are $[0,1]$.

Numerical calculations are performed in order to analyze and optimize the performance of the thermoelectric refrigerator driven by a thermoelectric generator. In the calculations, T_{H1} = 450 K, T_{L1} = 300 K, T_{H2} = 300 K, T_{L2} = 290 K, k_{H1} = 60 W/K, k_{L1} = 15 W/K, k_{H2} = 240 W/K, k_{L2} = 120 W/K, $\alpha = 2.1 \times 10^{-4}$ V/K, $K = 1.6 \times 10^{-2}$ W/K, and $R = 1.2 \times 10^{-3}\ \Omega$ are set [53].

4.2. Effects of total number and allocation of thermoelectric elements

The system working electrical current (I), cooling load (Q_{L2}) and COP (ε) vs. ratio of numbers of thermoelectric elements (x) are shown in Fig. 2 by solid lines, respectively. In the calculations, $M = 200$, $F = 1\ m^2$, $f = 0.6$, $f_1 = 0.7$, and $f_2 = 0.4$ are set. There exist two optimum working electrical currents corresponding to maximum cooling load ($Q_{L2,\max}$) and maximum COP ($\varepsilon_{\max}$). The maximum cooling load and maximum COP vs. the total number of thermoelectric elements (M) are shown in Fig. 3a and b by solid lines, respectively. In order to compare the results obtained by using the combination of finite time thermodynamics and

non-equilibrium thermodynamics with these obtained by using non-equilibrium thermodynamics, the non-equilibrium thermodynamic results, i.e. the effects of heat transfer are not taken into account, are also shown in Figs. 2 and 3 by dotted lines. One can see that the effects of heat transfer are obvious and should be considered in the performance analysis and optimization of the combined irreversible thermoelectric devices.

The optimum working electrical current ($I_{opt,Q_{L2}}$) corresponding to maximum cooling load ($Q_{L2,\max}$) and the optimum working electrical current ($I_{opt,\varepsilon}$) corresponding to maximum COP ($\varepsilon_{\max}$) vs. the total number of thermoelectric element pairs (M) are shown in Fig. 3c.

One can see that the optimum working electrical current (I) is smaller and no longer proportional to x when effects of heat transfer are taken into account. I increases monotonically and the slope of the curve decreases monotonically with the increase of x. I changes little when x is near 1.

Practical cooling load (Q_{L2}) and COP (ε) is smaller. The minimum x, i.e. the ratio of number of thermoelectric elements corresponding the zero cooling load and zero COP is bigger when the effects of heat transfer are taken into account. However, heat transfer has little influence on optimum x, i.e. the ratios of number of thermoelectric elements corresponding the maximum cooling load and maximum COP.

The maximum cooling load ($Q_{L2,\max}$) is smaller and no longer proportional to M when the effects of heat transfer are taken into account. $Q_{L2,\max}$ increases monotonically and the slope of curve decreases monotonically with the increase of M. The maximum COP ($\varepsilon_{\max}$) is no longer constant and decreases monotonically with the increase of M.

Both the optimum working currents $I_{opt,Q_{L2}}$ and $I_{opt,\varepsilon}$ decrease with the increase of total number of thermoelectric elements, and $I_{opt,Q_{L2}} \geqslant I_{opt,\varepsilon}$ holds.

4.3. Effects of total heat transfer area and allocation heat transfer area

Fig. 4 shows contour lines of the cooling load (Q_{L2}) and the COP (ε) vs. the heat transfer surface area ratios f_1 and f_2, respectively, with $M = 100$, $F = 1\ \text{m}^2$, and $f = 0.6$.

One can see that there are an optimum f_1 and an optimum f_2 corresponding maximum cooling load $Q_{L2,\max}$ or maximum COP $\varepsilon_{\max}$, respectively. In fact, for fixed total number of thermoelectric elements M and total heat transfer area F, there are optimum parameters x, f, f_1 and f_2 corresponding the maximum cooling load $Q_{L2,\max}$ or maximum COP $\varepsilon_{\max}$, respectively.

Fig. 5 shows the maximum cooling load $Q_{L2,\max}$, the maximum COP $\varepsilon_{\max}$, the optimum working electrical current ($I_{opt,Q_{L2}}$) corresponding to maximum cooling load, and the optimum working electrical current ($I_{opt,\varepsilon}$) corresponding to maximum COP vs. the total heat transfer surface area F, respectively, with $M = 100$. One can see that both the maximum cooling load and COP increases monotonically with the increase of F. The optimum working currents $I_{opt,Q_{L2}}$ increases with the increase of total heat transfer area F while $I_{opt,\varepsilon}$ changes little and $I_{opt,Q_{L2}} \geqslant I_{opt,\varepsilon}$ holds.

Calculations show that when total heat transfer area changes, the optimum variables x, f, f_1 and f_2 remain constant approximately.

5. Conclusion

A model of internal and external irreversible thermoelectric generator-driven thermoelectric refrigerator is presented in this paper by using a combination of finite time thermodynamics and non-equilibrium thermodynamics. Two analytical formulae describing the cooling load vs. working electrical current, and the coefficient of performance (COP) vs. working electrical current are derived. The performance optimization of the combined device is performed by searching for the optimum allocation of heat transfer surface area of the four heat exchangers and the optimum allocation of the number of thermoelectric element pairs based on the optimization of working electrical current. All the parameters should be considered in the design and application of practice thermoelectric devices in order to obtain the maximum economy benefit.

The results show that when effects of heat transfer are taken into account, the working electrical current is smaller than that by non-equilibrium thermodynamics. The cooling load is smaller and no longer proportional to total number of thermoelectric elements while the COP is no longer constant and decreases monotonically with the increase of total number of thermoelectric elements.

For the fixed total number of thermoelectric elements and total heat transfer surface area, there are optimum variables, i.e. ratio of numbers of thermoelectric element pairs x, total heat transfer surface area ratio f, generator heat transfer surface area ratio f_1 and refrigerator heat transfer surface area ratio f_2, corresponding the maximum cooling load or maximum COP, respectively.

Heat exchangers are necessary in thermoelectric generator-driven thermoelectric refrigerator devices. There is always external heat transfer loss in the devices. Conventional non-equilibrium thermodynamic analysis cannot take into account the external heat transfer factor. The combination of finite time thermodynamics and non-equilibrium thermodynamic gives a comprehensive analysis and optimization of the devices by taking account of external and internal irreversibilities and obtains optimal performance characteristics closer to practice. The results obtained herein may provide guidelines for the design and application of practical combined thermoelectric devices. Some experiments will be made to confirm the performance of the combined device in the later work by the way of Ref. [53].

Acknowledgements

This paper is supported by Program for New Century Excellent Talents in University of PR China (Project No. NCET-04-1006) and The Foundation for the Author of National Excellent Doctoral Dissertation of PR China (Project No. 200136). The authors wish to thank the reviewers for their careful, unbiased and constructive suggestions, which led to this revised manuscript.

References

[1] Angrist SW. Direct energy conversion. 4th ed. Boston: Allyn and Bacon Inc.; 1992.
[2] di Salvo FJ. Thermoelectric cooling and power generation. Science 1999;285(5428):703–6.
[3] Ma X, Riffat SB. Thermoelectric: a review of present and potential applications. Appl Therm Eng 2003;23(8):913–35.
[4] Bejan A. Advanced engineering thermodynamics. 2nd ed. New York: Wiley; 1997.
[5] Sisman A, Yavuz H. The effect of Joule losses on the total efficiency of a thermoelectric power cycle. Energy 1995;20(6):573–6.
[6] Chen J, Yan Z. The influence of Thomson effect on the maximum power output and maximum efficiency of a thermoelectric generator. J Appl Phys 1996;79(11):8823–8.
[7] Chen J, Yan Z, Wu L. Non-equilibrium thermodynamic analysis of thermoelectric device. Energy 1997;22(10):979–85.
[8] Rowe DM, Min G. Evaluation of thermoelectric modules for power generation. J Power Sour 1998;73(2):193–8.
[9] Omer SA, Infield DG. Design optimization of thermoelectric a devices for solar power generation. Solar Energy Mater Solar Cell 1998;53(1):67–82.
[10] Mayergoyz ID, Andrel D. Statistical analysis of semiconductor devices. J Appl Phys 2001;90(6):3019–29.
[11] Naji M, Alata M, Al-Nimr MA. Transient behavior of a thermoelectric device. Proc IMechE Part A: J Power & Energy 2003;217(6A):615–21.

[12] Nuwayhid RY, Shihadeh A, Ghaddar N. Development and testing of a domestic woodstove thermoelectric generator with natural convection cooling. Energy Convers Mgnt 2005;46(9–10):1631–43.
[13] Yu JL, Zhao H. A numerical model for thermoelectric generator with the parallel-plate heat exchanger. J Power Sour 2007;172(1):428–34.
[14] Huang BJ, Chin CJ, Duang CL. A design method of thermoelectric cooler. Int J Refrig 2000;23(3):208–18.
[15] Gordon JM, Ng KC, Chua HT, Chakraborty A. The electro-absorption chiller: a miniaturized cooling cycle with applications to micro-electronics. Int J Refrig 2002;25(8):1025–33.
[16] Chua HT, Ng KC, Xuan XC. Temperature-entropy formulation of thermoelectric thermodynamic cycles. Phys Rev E 2002;65(5):056111.
[17] Dai YJ, Wang RZ, Ni L. Experimental investigation on a thermoelectric refrigerator driven by solar cell. Renew Energy 2003;28(9):949–59.
[18] Yang R, Chen G, Kumar RA, Snyder GJ, Fleurial JP. Transient cooling of thermoelectric coolers and its applications for microdevices. Energy Convers Mgnt 2005;46(9-10):1407–21.
[19] Cheng YH, Lin WK. Geometric optimization of thermoelectric coolers in a confined volume using genetic algorithms. Appl Therm Eng 2005;25(17/18):2983–97.
[20] Chakraborty A, Saha BB, Koyama S, Ng KC. Thermodynamic modeling of a solid state thermoelectric cooling device: Temperature–entropy analysis. Int J Heat Mass Trans 2006;49(19-20):3547–54.
[21] Wang P, Bar-Cohen A, Yang B, Solbrekken GL, Shakouri A. Analytical modeling of silicon thermoelectric microcooler. J Appl Phys 2006;100(1):014501.
[22] Chakraborty A, Saha BB, Koyama S, Ng KC. Thin-film thermoelectric cooler: thermodynamic modeling and its temperature-entropy flux formulation. Proc IMechE, Part E: J Process Mech Eng 2007;221(1):33–46.
[23] Abramzon B. Numerical optimization of the thermoelectric cooling devices. ASME Trans J Electron Packag 2007;129(3):339–47.
[24] Lee KH, Kim OJ. Analysis on the cooling performance of the thermoelectric micro-cooler. Int J Heat Mass Trans 2007;50(9-10):1982–92.
[25] Pan Y, Lin B, Chen J. Performance analysis and parametric optimal design of an irreversible multi-couple thermoelectric refrigerator under various operating conditions. Appl Energy 2007;84(9):882–92.
[26] Chen X, Lin B, Chen J. The parametric optimum design of a new combined system of semiconductor thermoelectric devices. Appl Energy 2006;83(7):681–6.
[27] Khattab NM, El Shenawy ET. Optimal operation of thermoelectric cooler driven by solar thermoelectric generator. Energy Convers Mgnt 2006;47(4):407–26.
[28] Andresen B, Berry RS, Ondrechen MJ, Salamon P. Thermodynamics for processes in finite time. Acc Chem Res 1984;17(8):266–71.
[29] Feidt M. Thermodynamique et optimisation energetique des systems et procedes. 2nd ed. Lavoisier, Paris: Technique et Documentation; 1996.
[30] Bejan A. Entropy generation minimization: the new thermodynamics of finite-size devices and finite-time processes. J Appl Phys 1996;79(3):1191–218.
[31] Berry RS, Kazakov VA, Sieniutycz S, Szwast Z, Tsirlin AM. Thermodynamic optimization of finite time processes. Chichester: Wiley; 1999.
[32] Chen L, Wu C, Sun F. Finite time thermodynamic optimization or entropy generation minimization of energy systems. J Non-Equil Thermodyn 1999;24(4):327–59.
[33] Gordon JM, Ng KC. Cool thermodynamics. Cambridge, UK: Cambridge Int. Science Publishers; 2000.
[34] Durmayaz A, Sogut OS, Sahin B, Yavuz H. Optimization of thermal systems based on finite-time thermodynamics and thermoeconomics. Progr Energy Combust Sci 2004;30(2):175–217.
[35] Chen L, Sun F. Advances in finite time thermodynamics: analysis and optimization. New York: Nova Science Publishers; 2004.
[36] Sun F, Chen W, Chen L. Finite time thermodynamic criteria for optimization of the thermoelectric generator. Chin J Eng Thermophys 1993;14(1):13–5 [in Chinese].
[37] Gordon JM. Generalized power versus efficiency characteristics of heat engines: the thermoelectric generator as an illustration. Am J Phys 1991;59(5):551–5.
[38] Wu C. Heat transfer effect on the specific power availability of heat engines. Energy Convers Mgnt 1993;34(10):1239–47.
[39] Agrawal DC, Menon VJ. The thermoelectric generator as an endoreversible Carnot engine. J Phys D: Appl Phys 1997;30(2):357–9.
[40] Chen J. Thermodynamic analysis of a solar-driven thermoelectric generator. J Appl Phys 1996;79(5):2717–21.
[41] Chen J, Andresen B. New bounds on the performance parameters of a thermoelectric generator. Int J Pow Energy Syst 1997;17(1):23–7.
[42] Chen J, Wu C. Analysis on the performance of a thermoelectric generator. Trans ASME J Energy Resour Technol 2000;122(1):61–3.
[43] Chen L, Gong J, Sun F, Wu C. Effect of heat transfer on the performance of thermoelectric generators. Int J Therm Sci 2002;41(2):95–9.
[44] Chen J, Lin B, Wang H, Lin G. Optimal design of a multi-couple thermoelectric generator. Semicond Sci Technol 2000;15(2):184–8.
[45] Crane DT, Jackson GS. Optimization of cross flow heat exchangers for thermoelectric waste recovery. Energy Convers Mgnt 2004;45(9-10):1565–82.
[46] Chen L, Sun F, Wu C. Thermoelectric generator with linear phenomenological heat transfer law. Appl Energy 2005;81(4):358–64.
[47] Chen L, Sun F, Wu C. Heat transfer surface area optimization for a thermoelectric generator. Int J Ambient Energy 2007;28(3):135–42.
[48] Chen M, Rosendahl L, Bach I, Condra T, Pedersen J. Irreversible transfer processes of thermoelectric generators. Am J Phys 2007;75(9):815–20.
[49] Goktun S. Design consideration for a thermoelectric refrigerator. Energy Convers Mgnt 1995;36(10):1197–200.
[50] Goktun S. Optimal performance of a thermoelectric refrigerator. Energy Sour 1996;18(4):531–6.
[51] Chen L, Wu C, Sun F. Heat transfer effect on the specific cooling load of refrigerators. Appl Therm Eng 1996;16(12):989–97.
[52] Xuan XC, Ng KC, Yap C, Chua HT. A general model for studying effects of interface layers on thermoelectric devices performance. Int J Heat Mass Trans 2002;45(26):5159–70.
[53] Chen L, Gong J, Sheng L, Sun F, Wu C. Theoretical analysis and experimental confirmation of the performance of a thermoelectric refrigerator. J Non-Equil Thermodyn 2001;26(1):85–92.
[54] Xuan XC. Optimum design of a thermoelectric device. Semicond Sci Technol 2002;17(2):114–9.
[55] Chen K, Lin GT. Optimization of multiple-module thermoelectric coolers using artificial-intelligence techniques. Int J Energy Res 2002;26(14):1269–83.
[56] Xuan XC. Investigation of thermal contact effect on thermoelectric coolers. Energy Convers Mgnt 2003;44(3):399–410.
[57] Luo J, Chen L, Sun F, Wu C. Optimum allocation of heat transfer surface area for cooling load and COP optimization of a thermoelectric refrigerator. Energy Convers Mgnt 2003;44(18):3197–206.